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A review of wireless body area networks

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ABSTRACT

The widespread adoption of wireless body area network (WBAN) in healthcare presents opportunities to meet the increasing demand for medical services. WBAN enables continuous real-time (RT) monitoring through biomedical sensor nodes positioned in or around a patient's body, collecting vital physiological data. In addition, WBAN imposes stringent criteria for energy efficiency and reliability throughout data collection and transmission. This review paper places significant emphasis on the fundamental concept and essential characteristics of WBAN technology. First, the WBAN features, including architecture, sensor nodes types and network topology is presented. Then, the study explores a wide variety of communication standards and multiple access (MA) mechanism deployed in this technology. Moreover, it discusses open research and challenging issues such as heterogeneous traffic, quality of services (QoS), energy consumption, reliability, interference management, and human body movements effect. Finally, the paper is concluded, and future directions are identified in this evolving field of human health monitoring technology.

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1. INTRODUCTION

The wireless body area network (WBAN) is a specialized network designed for in-body and on-body communication, setting it apart as a sub-class of the wireless sensor network (WSN) with both similarities and significant distinctions [1]. Typically, WSN does not tackle the specific challenges related to health monitoring. On the other hand, WBAN holds immense potential for enhancing wearable computing applications and e-healthcare technology. WBAN offer continuous monitoring capabilities for a specific duration and can handle real-time (RT) traffic, including data, voice, and video, enabling the observation of vital organ functionality [2]. The biomedical sensor nodes deployed for WBAN, comprising communication boards and antennas, transmit data to a medical system, which then displays, stores, and analyzes the information to identify any medical abnormalities. As these sensor nodes are battery-powered devices with a limited lifespan, a malfunctioning battery leads to the cessation of WBAN operation [3]. Consequently, ensuring energy efficiency becomes crucial for extending the lifespan of sensor nodes. The primary distinguishing characteristic of WBAN lies in their ability to prolong network lifetime by implementing efficient low-power techniques on energy-constrained sensor nodes [4].

The internet and established wireless technologies, such as Bluetooth, WSN, ZigBee (IEEE 802.15.4), wireless local area networks (WLAN), wireless personal area networks (WPAN), video

surveillance systems, and cellular networks can be interfaced with WBAN. IEEE 802.15.6, which defines a standard for low-power, short-range, and highly dependable wireless communication within the human body, is the most recent WBAN standard. Therefore, WBAN is considered a pivotal technology for providing healthcare services at any time or place and is expected to have a significant impact on raising people's quality of life. WBAN systems and architectures require a thorough examination of several requirements. The medium access control (MAC) layer is crucial to meet WBAN concerns such as resource allocation, protocol overhead, collision prevention, overhearing, idle listening, packet delay, congestion control, reliability, retransmission, and congestion control [5]. Thus, its design significantly impacts overall WBAN performance [6].

This review paper highlights the overall framework of WBAN communication, encompassing its architecture, sensor node types, network topology, and the relevant communication standards, namely IEEE 802.15.4 and IEEE 802.15.6. Additionally, the review explores various multiple access (MA) mechanisms designed to address the unique requirements and constraints of WBAN. Furthermore, this study identifies and discusses the open research challenges inherent to WBAN, thereby contributing valuable insights into the direction of future studies in this field.

2. WBAN FEATURES

This section discusses an in-depth exploration of the WBAN features, delving into its architecture, sensor node variations, and network topology. Furthermore, it examines the interconnection of sensor nodes in the network. Placing particular emphasis on the significance of achieving efficient and reliable data transmission within WBAN network.

2.1. WBAN architecture

The communication architecture of WBAN, as depicted in Figure 1, encompasses three distinct functioning sections, each playing a crucial role in enabling effective data transmission and communication within the network [7], [8]:

i) Tier–1: the intra-WBAN section focuses on communication within the WBAN. This tier involves interactions among biomedical sensor nodes, enabling them to measure and exchange information among themselves and with the coordinator. Wireless communication standards like Bluetooth, low-rate WPAN (LR-WPAN) (802.15.4), and WBAN (802.15.6) are commonly utilized for collecting and transmitting data from the sensor nodes to the coordinator [9].

ii) Tier–2: the inter-WBAN section handles communication between the intra-BAN coordinator and other entities, such as the access point (AP), multiple co-existing BANs, and enables body-to-body (B2B) communication. This tier establishes connectivity, facilitates data exchange between different WBAN, and supports communication between WBAN and external systems or devices.

iii) Tier-3: beyond-WBAN represents the communication that extends beyond the boundaries of individual BAN. In this tier, the AP serves as a bridge, transmitting data packets from the WBAN to the corresponding health center or destination using the internet or other communication mediums.

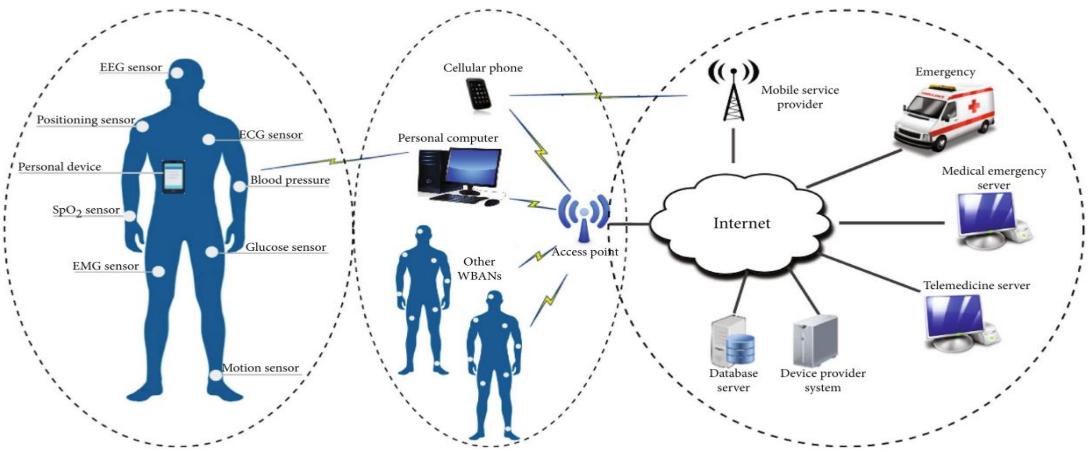

Figure 1. WBAN architecture [10]

2.2. WBAN sensor nodes

In the context of WBAN, sensor nodes can be classified into two distinct classes based on their functionality and implementation. These classifications are essential for understanding the diverse roles and capabilities of the nodes within the network. The categorization of sensor nodes is as follows:

i) Coordinator*:* in the WBAN system, the coordinator is called the hub, sink, or personal device (PD). As the network's central control point, it oversees user interactions and gathers data from other sensor nodes. The coordinator is in charge of collecting information and delivering it to the user via various channels, including an external gateway, a display interface, or indicators built right into the device, like light emitting diodes (LEDs). Depending on the particular setting and implementation of the WBAN system, it can be referred to by one or more of the following names: body gateway, sink, body control unit (BCU), or personal digital assistant (PDA).

ii) Sensor nodes: specific physiological parameters can be measured by the sensor nodes inside or outside the human body. These sensor nodes are essential in the communication process because they gather pertinent data, process physical signals, and wirelessly communicate responses. Applications for commercial sensor nodes in WBAN are numerous and include monitoring vital signs, including blood pressure, temperature, respiration rate, glucose level, electrocardiogram (ECG), electroencephalogram (EEG), and electromyography (EMG) [11], [12]. These sensor nodes are essential for WBAN-enabled healthcare systems because they supply precise RT data for analysis and monitoring. The three WBAN communication possibilities provide a range of applications and allow for the internal and external tracking of physiological indicators.

A WBAN is established by deploying sensor nodes in three distinct communication scenarios [13]. This encompasses the following:

i) On-body communication: this scenario incorporates wearable sensors placed on the human body's surface or in close vicinity, often a few centimeters distant.

ii) In-body communication: sensor nodes are implanted within the human body, either beneath the skin or within bodily tissue. These nodes are also known as implanted sensors.

iii) Off-body communication: in this scenario, sensor nodes are placed at a distance from the human body, ranging from a few centimeters to five meters. These nodes do not have direct physical contact with the human body, unlike the on-body and in-body scenarios.

2.3. WBAN network topology

WBAN network topologies are generally based on a star topology. The star topology employs single-hop, multi-hop, or two-hop configurations for communication [14]. In the single-hop star topology, sensor nodes establish direct connections with the BAN coordinator, as depicted in Figure 2. To improve communication between the coordinator and sensor nodes, a relay node is added to the multi-hop star architecture. It can be accomplished through direct communication or by relaying the data through the intermediary relay node. Regarding the MAC sub-layer settings, the IEEE 802.15.6 standard specifies that a single BAN must have only one coordinator [15]. A BAN can have any number of sensor nodes between 0 to *nMaxBANSize*, with 64 nodes being the maximum number allowed by the standard. This ensures a well-defined and manageable network structure within the BAN, enabling efficient coordination and communication among the sensor nodes and the BAN coordinator.

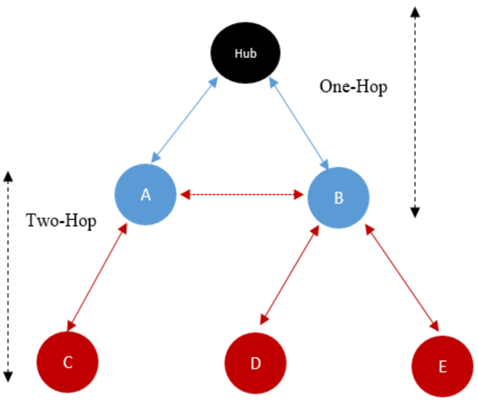

Figure 2. WBAN network topology [16]

3. WBAN COMMUNICATION STANDARDS

The IEEE 802.15.4 and IEEE 802.15.6 standards are two key references for the MAC superframe structure that is used in the design of MAC protocols for WBAN applications [3], [17]. These standards offer the framework for specifying the MAC superframe's structure, which can be modified to meet the unique needs and functional traits of WBAN. The IEEE 802.15.6 standard plays a significant role as it explicitly specifies the physical (PHY) and MAC layer specifications for WBAN [18]. It is important to remember that other protocols, such as WLAN, IEEE 802.15, and Bluetooth, lack the capabilities and optimizations of WBAN requirements and must be more appropriate for use in the healthcare industry. Thus, according to IEEE 802.15.4 and IEEE 802.15.6 standards, one of the most important design choices for MAC protocols in WBAN is the MAC superframe structure.

3.1. IEEE 802.15.4 standard

Published in 2006 [19], the IEEE 802.15.4 task group 4 (TG4) communication standard is primarily intended for low-power and low-data-rate applications. This standard supports WSN and WBAN applications. Beacon-enabled mode and non-beacon-enabled mode are the two operating modes for this standard. Figure 3 provides a general overview of the MAC superframe structure of IEEE 802.15.4 in the beacon-enabled mode. There are active and inactive parts of the superframe. Furthermore, there are 16 equal time slots for data transmission throughout the active period. The contention access period (CAP), contention free period (CFP), and beacon comprise this superframe. Time division multiple access (TDMA) is the method used by the CFP. The carrier sense multiple access/collision avoidance (CSMA/CA) technique is employed in the CAP, in contrast to the CFP. Following the CAP and CFP phases, the sensor nodes and body coordinator enter a sleep mode for the inactive period. The non-beacon-enabled mode does not define the superframe, the slot synchronization, or the guarantee time slot (GTS). However, for medium sharing, only the random-access mechanism is employed. The data transmission for this operation mode uses the unslotted CSMA/CA mechanism. The major disadvantage of IEEE 802.15.4 is the limited GTS for collision-free transmission, which is impractical for WBAN applications [20]. Also, the heterogeneous nature of data is additionally forbidden by this standard, making it unsuitable for transmitting emergency data.

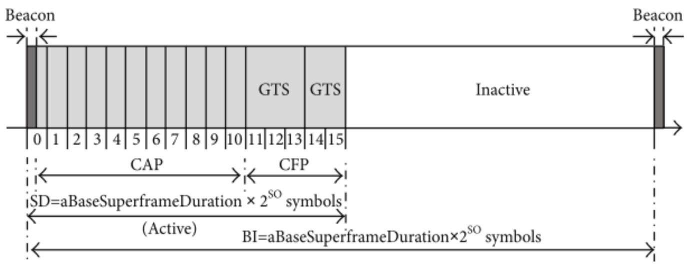

Figure 3. Beacon-enabled mode superframe structure [19]

3.2. IEEE 802.15.6 standard

IEEE 802.15.6 is a standard released in 2012 by IEEE task group 6 (TG6) to standardize communication among sensor devices connected to a wireless backhaul network [15]. This standard can be employed in numerous medical and non-medical fields. It operates at ultra-low-power, low complexity, high reliability, short-range wireless communication inside or close to the human body, and functioning at low frequencies [21].

IEEE 802.15.6 specifies that the MAC layer supports three PHY layers: human body communication (HBC), ultra-wideband (UWB), and narrowband (NB) [22]. The NB and UWB are based on radio frequency (RF) propagation, whereas the HBC is based on the non-RF method [23]. The NB-PHY supports seven frequency bands: 402-2483.5 MHz for 230 channels, 402-405 MHz for implantable devices, and 2360-2400 MHz for medical applications. The frequency range that the UWB-PHY supports is 3494.4-9984 MHz. The HBC-PHY has a frequency range of 5 to 50 MHz with a core frequency of 21 MHz. The PHY layer of this standard manages the following tasks: radio transceiver activation and deactivation, clear channel assessment (CCA) for the current channel, and data transmission and reception. The chosen PHY layer depends on the aim of applications-medical or non-medical and within, outside, or off the human body [23]. The essential technical requirements of the IEEE 802.15.6 standard can be outlined as [24], [25]:

i) Under typical conditions, a WBAN is capable of supporting links with a maximum throughput of 10 kbps. However, non-medical applications could need transmission rates of up to 10 Mbps, but medical applications require a modest data rate of less than 300 kbps.
ii) For a 256-octet payload, the packet error rate (PER) for 95% of the top-performing links should be less than 10%.
iii) Dependability, delay, and jitter should be prioritized in WBAN applications. For non-medical applications, both delay and jitter should be minimized below 250 ms. On the other hand, fewer than 125 ms of delay is required for medical applications.
iv) WBAN needs to be able to work in a heterogeneous setting with various devices and technologies.
v) Power-saving measures should be taken to allow WBAN to function effectively when there is a power shortage.
vi) To guarantee dependable and effective communication, WBAN must have quality of service (QoS) management features and prioritize service.
vii) WBAN should be able to coexist within range, both in-body and on-body. Even when the user moves, sensor nodes must be able to continue having dependable connectivity.

The beacon mode with a beacon-period superframe, the non-beacon mode with a superframe, and the non-beacon mode without a superframe are the three modes of operation defined by the IEEE 802.15.6 standard. Since it synchronizes transmission between multiple sensing devices, the beacon mode with a beacon-period superframe is the most practical option. The IEEE 802.15.6 superframe structure in beacon-enabled mode, which is expected to handle diverse traffic loads, is shown in Figure 4. The exclusive access phase (EAP 1 and EAP 2), the random-access phases (RAP 1 and RAP 2), the manage access phases (MAP 1 and MAP 2), the CAP, and two beacon frames (B) make up its nine distinct phases. In practice, the MAC superframe can be modified by turning on or off any access phase [26]. The IEEE 802.15.6 WBAN specifications standard states that the RAP and CAP are set aside for normal data, whereas the EAP is intended for the highest-priority data [27]. In addition, the MAP phases are offered for allocated bilink, uplink, and downlink schedules. Additionally, as shown in Table 1, the IEEE 802.15.6 standard offers eight distinct user priorities (UPs) for various types of traffic.

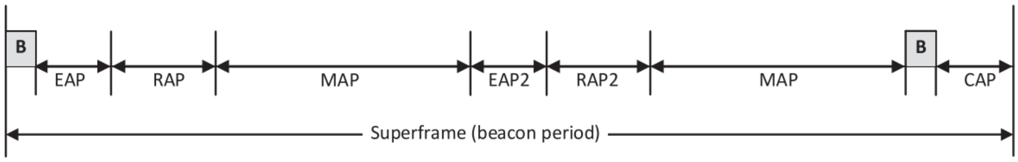

Figure 4. Beacon mode with beacon period superframe [15]

Table 1. UP mapping [15]

Priority	(UP)	Traffic designation	Frame type
Lowest	0	Background (BK)	Data
	1	Best effort (BE)	Data
	2	Excellent effort (EE)	Data
	3	Voice (VO)	Data
	4	Video (VI)	Data
	5	Medical data or network	Data and management
	6	High priority medical data or network control	Data and management
Highest	7	Emergency or medical implant and even report	Data

4. WBAN MULTIPLE ACCESS MECHANISM

In the MAC protocols for WBAN, the allocation of slots for sensor nodes is facilitated through various MA mechanisms. These mechanisms include CSMA/CA, TDMA, frequency division multiple access (FDMA), and slotted aloha. The MAC layer utilizes these MA techniques to enable efficient channel access for sensor nodes. There are three main categories of MA schemes used in WBAN at the MAC layer: contention-based, schedule-based, and hybrid-based, along with polling/low-power listening (LPL) methods [28], [29]. Table 2 provides a comprehensive comparison of different MA mechanisms. The adoption of MA mechanisms helps in the allocation of channels for heterogeneous data from patients. Various MA techniques have been employed to enhance throughput, optimize channel utilization, fast and accurate data transfer, and minimize collision, delay, retransmission, and energy consumption.

4.1. Contention-based slots allocation (CSMA/CA)

The most used scheme is CSMA/CA due to its ease of deployment and scalability. The first come, first served (FCFS) principle supports the slot allocation scheme for body sensor nodes employed by the CSMA/CA scheme [30]. This scheme has no reserved time slots for the channel [31]. Before transmitting data, every sensor node listens to the channel to determine if it is idle. The sensor node initiates the data transfer if the channel is reachable. If no channel is available, the sensor node will back off and try again. Therefore, the main shortcoming of CSMA/CA is the wastage of energy consumption for protocol overhead and collision avoidance [32]. Despite this, the advantage of contention-based slot allocation includes low delay, low complexity, effective traffic load adaptation, and reliable WBAN data transmission. For WBAN with a low traffic volume and frequent network changes, CSMA/CA is more effective.

4.2. Schedule-based slots allocation (TDMA/FDMA)

Schedule-based slot allocations such as TDMA and FDMA assign a set number of time slots with a predetermined frame length to the channel connection of the sensor nodes [33]. Every sensor node can be allocated for numerous time slots, depending upon its requirements and volume of data. Collision can be circumvented, since sensor nodes only transmit during their designated time slots. In this approach, to guarantee that the sensor nodes broadcast their packets inside the designated periods, each sensor node needs to be synchronized using different control messages. Thus, the main drawback of schedule-based MAC protocols is synchronization issues [34]. In terms of throughput, bandwidth usage, and energy efficiency, TDMA outperforms CSMA/CA [35]. This scheme is well-suited for networks with high periodic traffic volume and infrequent network changes.

4.3. Hybrid-based slots allocation

Hybrid-based slot allocation combines schedule-based schemes, such as TDMA, with contention-based techniques like CSMA/CA, resulting in MAC protocols that aim to leverage the advantages of both approaches [7]. Nevertheless, the hybrid MAC protocols get more complex when these two techniques are combined. Furthermore, more control packets are needed to switch between schedule-based and contention-based methods, which increases network traffic and energy usage. Therefore, while hybrid-based slot allocation offers better performance, it comes with the trade-off of higher resource consumption and protocol complexity.

4.4. Polling/low-power listening

Sensor nodes periodically awaken as part of the polling/LPL access mechanism to observe channel activity without actively receiving data packets. When the channel is found to be empty, the sensor nodes enter a sleeping mode to conserve energy. However, if the channel is active, the sensor nodes keep their transceivers in active mode to receive incoming data packets. By employing polling techniques, overhearing can be minimized, and synchronization requirements are reduced. Nevertheless, one drawback of the polling approach is the increased energy consumption during the transmission and reception of long preambles, which can impact overall energy efficiency.

Table 2. Comparison of different MA mechanism

Access mechanism	Reliability support	Energy efficiency	Synchronization	Transmission efficiency	Delay
Contention-based	Good	High	-	Low	Variable
Scheduling-based	Good	Low	Necessary	High	Fixed
Polling-based	Good	Moderate	Necessary	High	Fixed
Hybrid-based	Good	High	-	Variable-fixed	Variable-fixed

5. WBAN RESEARCH CHALLENGES

WBAN faces numerous challenges that could hinder its performance. Ensuring the effective operation of WBAN applications necessitates the resolution of substantial challenges within the design of MAC protocols. In this section, some of the challenges highlighted in existing literature will be elucidated.

5.1. Heterogeneous traffic

WBAN traffic is inherently heterogeneous, as it involves multiple sensor nodes monitoring diverse vital information within the network. As a result, there are variations in data rate, frequency, and computing energy among the sensor nodes. Certain applications necessitate RT traffic, while periodic traffic measurements suffice for others. Traditional MAC protocols that allocate fixed time slots must be revised to meet the demands of heterogeneous and dynamic traffic in WBAN. Thus, a dynamic slot allocation approach

must be incorporated into the MAC protocols. One potential solution to this challenge is the use of an adaptive superframe structure, which takes the UP into account when managing the varied traffic. This approach prevents inefficient utilization of the superframe period and ensures the MAC protocols cater to the specific requirements for each traffic category in WBAN.

Wang *et al*. [36] presented the all dynamic-MAC (AD-MAC) protocol, which uses dynamic length allocation, dynamic time slot allocation, and dynamic priority management to maximize the superframe throughout different access periods. Reliable data transmission with minimum energy usage and less delay is the goal of this strategy. A modified superframe structure is incorporated into the IEEE 802.15.6-based adaptive-MAC (A-MAC) protocol [37]. When traffic volume changes, the A-MAC dynamically adjusts time slot allocation, improving energy efficiency and traffic adaptation. Additionally, Azhar *et al*. [38] presents the drop packet estimation (PDE) approach, a dynamic superframe adjustment mechanism based on the IEEE 802.15.6 standard. When there is no emergency traffic, the PDE adjusts the duty cycle based on packet drops to minimize the use of communication channels and avoid channel waste. Furthermore, Saboor *et al*. [39] introduces a dynamic slot allocation mechanism that better uses the IEEE 802.15.6 superframe by minimizing destruction caused by fixed slot sizes, reducing delay, and increasing network throughput. This mechanism uses a non-overlapping contention window. An IEEE 802.15.4 superframe structure modification is the foundation for the priority adaptive-MAC (PA-MAC) protocol introduced [40]. This MAC protocol dynamically allocates time slots based on traffic priority. However, one significant disadvantage of the PA-MAC is that it performs worse when there is no GTS, especially when there are high and heavy traffic loads.

5.2. Quality of service

To achieve differentiated QoS, optimization of various MAC parameters is essential. The coordinator should be able to selectively allocate radio resources to each sensor node based on their traffic priorities, thereby providing high priority traffic with differential QoS [41]. For instance, emergency or critical traffic can be better supported by allocating more dedicated time slots to the sensor nodes handling such crucial information. A fixed channel allocation approach may lead to performance degradation or resource waste, particularly because the on-body communication link experiences significant fluctuations [42]. To address this, differentiated QoS can be facilitated by improving the CSMA/CA-based channel contention mechanism. One approach is to dynamically determine the back-off bounds, which increases the probability of channel access for high priority traffic, thereby ensuring more efficient and responsive MAC protocols for WBAN applications.

To provide the desired QoS, a traffic-aware MAC (TA-MAC) protocol utilizes the IEEE 802.15.4 standard and dynamically distributes time slots following the traffic priority [43]. Furthermore, to meet the QoS needs of emergency traffic, a scheduling technique called priority-weighted round robin (PWRR) is created [44] based on the IEEE 802.15.6 standard. Priority scheduling and WRR are combined in this technique to improve QoS provisioning. Additionally, Ambigavathi and Sridharan [45] describe the energy efficient and load balanced priority queue (ELBPQ) algorithm, which tries to strengthen QoS requirements while lowering overhead, delay, and data rate. Nevertheless, a drawback of this algorithm is the inadequately balanced load among the queues, leading to high delay and energy consumption during critical data transmission. Samal and Kabat [46] propose the traffic prioritized load balanced scheduling (TPLBS) algorithm, designed to balance the load across different priority queues within the IEEE 802.15.6 standard. This work introduces an effective probabilistic priority-based scheduling method for ensuring reliable data transmission across multiple WBANs to improve delay, energy efficiency, throughput, and QoS. A MAC protocol is presented in [47] to address the issues with energy efficiency and QoS. Using a TDMA technique, this protocol enables dynamic changes to the transmission order and duration. Additionally, a new synchronization method is considered to reduce packet overhead.

5.3. Energy consumption

Energy consumption is a critical challenge in WBAN due to its severe resource constraints. These networks consist of battery-powered sensor nodes with limited processing and communication capacities, and the sensor nodes typically cannot have their batteries changed or recharged. Therefore, it is essential to minimize energy dissipation to enable continuous and long-term patient monitoring. The energy efficiency in WBAN can vary depending on the communication standards employed. Among these standards, IEEE 802.15.6 demonstrates a better successful packet transmission rate than IEEE 802.15.4 despite consuming more energy. In IEEE 802.15.6, the higher energy consumption can be attributed to the carrier detecting the channel and reducing the back-off counter based on the sensed channel conditions. Efforts to address energy consumption in WBAN are crucial to ensure the longevity of battery life and to optimize the network's overall performance.

A technique known as the improved packet scheduling mechanism (IPSM) is presented in [48] for the dynamic allocation of slots to the node. This method is suggested to prevent congestion, enhance energy

efficiency, and extend the network's lifetime because lower energy consumption extends the battery life of network sensing devices. Moreover, to lower energy consumption and delay in the WBAN network, the energy consumption traffic prioritization-MAC (ECTP-MAC) protocol is proposed [20]. In addition, an energy-efficient traffic prioritization-MAC (EETP-MAC) protocol is introduced [49] to provide adequate traffic prioritization. By allocating specific slots to different types of traffic inside the communication network, the proposed approach can reduce energy consumption.

5.4. Reliability

Reliability is paramount in WBAN as it directly impacts human health monitoring. Maintaining the effectiveness of end-to-end communication and the quality of network connectivity requires a highly stable network. Reliability can be evaluated by assessing factors such as fault tolerance, QoS, and security in network communication. By addressing these aspects, a reliable WBAN can be established, meeting the requirements for a dependable network that satisfies user expectations and ensures the well-being of human monitoring [50].

The MAC protocol improves communication dependability when different human activities cause interference in the RF spectrum [51]. The MAC protocol enhances reliability and energy efficiency by evaluating the dynamic nature of human activities using packet delivery rate (PDR) and received signal strength information (RSSI). By using a relay node, the proposed MAC protocol seeks to achieve high PDR and communication reliability. However, adding a relay node increases energy consumption, which shortens the sensors' lifespan. The conventional TDMA techniques used in WBAN standards, such as IEEE 802.15.4 and IEEE 802.15.6, ignore node dependability and channel circumstances. Their use of static slot allocation is the cause of this error, which has two serious consequences. Initially, even in cases where links experience profound fading, every node must utilize the designated time slots on the channel. Second, regardless of its unique requirements, every node in a TDMA round has an equal number of slots. As a result, uniform slot allocation is complex, and retransmission could be more efficient if a node experiences packet loss during the time slots owing to deep fading since deep fading lasts for a long time. To address this shortcoming, Salayma *et al*. [52] present two novel TDMA-based methods that enhance WBAN's dependability and energy efficiency. These methods address the channel link status and adaptively synchronize nodes.

5.5. Interference

Interference poses a significant challenge in WBAN and demands careful consideration. The transmission of medical data can suffer from delay or incompleteness caused by inter-WBAN interference, particularly in adjacent WBAN. The IEEE 802.15.6 standard addresses this issue by specifying that when multiple WBANs are co-located, the network should operate effectively within a transmission range of up to 3 meters to mitigate inter-WBAN interference [15]. Within a single WBAN, coordinating or combining various channel access techniques can effectively reduce intra-WBAN interference, enhancing the overall network performance and reliability [7]. Single-channel MAC protocols are inadequate for WBAN because they rely on a single channel, leading to interference, delay, energy inefficiency, and node collision. Consequently, various multi-channel MAC protocols have been developed to address these challenges.

To provide RT, dependable emergency traffic delivery, and maximize energy efficiency, Samal and Kabat [53] present a time-sharing multi-channel MAC protocol for WBAN. This work aims to create an efficient time-sharing multi-channel MAC protocol for WBAN that facilitates energy-efficient transmission while minimizing interference. Li *et al*. [54] describe the multi-channel MAC (MC-MAC) protocol, intended to reduce inter-WBAN signal interference and meet the urgent requirement for RT medical data transmission with minimum delay. The equitable distribution of traffic through many channels results in better performance, including lower delay and higher throughput. The two-tier multi-channel MAC (2TM-MAC) protocol is presented [55] to handle the coexistence of WBAN and provide high data transmission reliability and low delay for health monitoring requirements. There are two layers in the 2TM-MAC protocol. It allocates different interference-free channels to every WBAN in the first layer. Based on each node's unique traffic arrival rate, the hub distributes these channels to specific nodes for the second layer. This method improves network speed and channel utilization while minimizing data packet delay and interfering with other WBANs.

Based on IEEE 802.15.6 standards, the energy efficiency and low interference MAC (EI-MAC) protocol is a multi-channel MAC protocol intended for WBAN and was first introduced in [56]. There are eight channels in this protocol: one for control and seven for data. A metric is computed by considering variables like data volume, user priority, and residual energy to establish the node priority. Nevertheless, the EI-MAC has no dedicated channels allocated for transmitting emergency data. Previous study have introduced a hybrid multi-channel MAC (HM-MAC) protocol to mitigate interference issues within WBAN [57]. In HM-MAC, data packets can be transmitted using CSMA/CA and TDMA techniques. This approach enables

simultaneous communication on separate channels, minimizing collision and maximizing network throughput.

5.6. Body movements

Unpredictable body movements and posture changes pose a significant challenge for MAC protocols in WBAN as they can disrupt network performance [58]. However, cooperative communication through relay nodes offers a promising solution to manage outages caused by these changes. By leveraging relay nodes, traffic can be intelligently diverted to less congested routes, thereby improving PDR and overall network reliability [7]. This approach ensures that the impact of unpredictable body movements and posture changes on network performance is minimized, leading to more robust and stable communication in WBAN. The human body exhibits postural mobility in WBAN, which has been discussed as a factor leading to disconnections in work by Ramachandran *et al*. [51]. In mobility scenarios, sensor node connections experience instability due to changes in mobility and distance, resulting in the fading of RF channels for the sensor nodes.

6. FUTURE DIRECTION

Researchers have consistently strived to identify the most effective solutions to overcome the challenges associated with WBAN. In tackling these challenges, energy harvesting (EH) represents a promising technology that utilizes self-sustaining energy sources for WBAN. Despite numerous efforts to improve the energy efficiency of compact WBAN sensor nodes, incorporating EH technology in WBAN must deal with a few challenges, such as power allocation, source availability and design complexities. Nonetheless, EH is emerging as a critical method to enhance energy efficiency, especially as more functionalities are integrated into the sensor nodes. Another prominent issue arises from the risk of depending on a single-hop topology, as this network configuration may not provide the required reliability for WBAN communication. Reliable communication is important for monitoring vital signs, collecting health data, and delivering timely interventions. The implementation of multi-hop topology has the potential to deliver more reliable communication, which could significantly improve overall WBAN performance. Hence, conducting further research into the multi-hop topology may be a valuable pursuit for WBAN.

The MAC protocols for WBAN pose a wide range of research opportunities. Additionally, there is a need for dedicated communication protocols that carefully consider the unique characteristics of WBAN, where data packets must traverse relaying nodes to reach the coordinator. Potential avenues for exploration include MAC protocols that are QoS-aware, temperature-aware, multi-channel, and based on postural movement to address the specific requirements of WBAN. Furthermore, in the WBAN context, data processing represents another unexplored research domain within the internet of things (IoT). WBAN nodes produce a significant volume of data that must be securely stored and processed to ensure the security and privacy of patients. Additionally, the presence of multiple WBAN sensor nodes capturing identical physiological signals poses a data processing challenge. Consequently, there is a need to explore effective methods for processing big data and performing data fusion, offering potential avenues for research. Blockchain technology is gaining considerable interest as a viable option for boosting trust management in WBAN. Incorporating blockchain technology into trust management strategies for WBAN requires significant emphasis, particularly considering its potential benefits in data-centric approaches. Several essential aspects must be considered when integrating blockchain technology into WBAN, including mutual trust agreements, data management, controller management, and QoS.

7. CONCLUSION

In the healthcare domain, WBAN is an emerging area of research and development. Despite the significant potential of WBAN to provide various benefits to humans in the healthcare field, numerous critical issues need to be addressed. This review explores the architecture, various sensor node configurations, and the network topology of WBAN. Additionally, the review includes an analysis of different communication standards, focusing on the latest IEEE 802.15.6 standard customized for WBAN. Notably, the IEEE 802.15.6 standard introduces an energy-efficient approach that enables low-power and reliable communication, unlike the IEEE 802.15.4 standard, which consumes more energy and utilizes higher bandwidth. Furthermore, many MA techniques are examined, highlighting the importance of selecting MA mechanisms for WBAN. This evaluation should be based on the precise needs and constraints of the WBAN application, as these factors can affect efficiency, throughput, delay, reliability, scalability, interference management, and network adaptability. The proposed work addressed in the literature discusses various research challenges on WBAN. These challenges encompass various aspects of WBAN technology, including MAC protocols, energy efficiency, network reliability, body movement effect, interference, and

data management. By delving into these challenges, the literature not only identifies the current issues but also lays the groundwork for potential solutions and innovations. Therefore, researchers can draw valuable insights from assessing WBAN research challenges to advance the development of WBAN technology. This review is expected to offer essential guidance for achieving robust link-level communication in WBAN.

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